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Chapter

Use of Exoskeletons in the Treatment and Rehabilitation of Paraplegia Patients

Susana Martiñón and Ricardo Hernández-Miramontes

Abstract

This chapter presents a review that includes five robotic exoskeletons used in the rehabilitation of paraplegic patients, highlighting the qualities of each one and offering the doctor and the rehabilitator a tool to select the exoskeleton that is most appropriate to the needs of their patient and a more satisfying and integral therapy. A systematic search was carried out in different platforms of scientific interest, the publications that met the inclusion criteria were selected. The information collected was classified and synthesized, resulting in a review that covers the five most relevant exoskeletons for the rehabilitation of paraplegic patients. Concluding with a tool that helps the therapist select the most appropriate exoskeleton for each patient.

Keywords: paraplegia, rehabilitation, exoskeleton

1. Introduction

Paraplegia is the paralysis of the lower half of the body, affecting both legs; it is usually the result of spinal cord trauma [1, 2], however, it can also be caused by diseases such as ischemic events [3, 4], multiple sclerosis and amyotrophic lateral sclerosis among other neurodegenerative diseases, including Parkinson's disease [1].

The care of the patient with paraplegia must be integral, including medical, surgical, psychological treatment and finally rehabilitation by physiotherapy [5].

At this last point, various therapies have been developed, including the use of exoskeletons. Studies have determined that the uses of exoskeletons include: increasing human performance, improving mobility of individuals with neurological pathologies, and providing assistive technology for people with disabilities [6]. In this chapter, different exoskeletons that are in use are presented for the rehabilitation of patients.

For this chapter, a review was carried out in the search engines *PubMed, Google Academics, Elsevier, Science Direct and Medline*, finding 15 scientific papers that met the inclusion criteria.

Inclusion criteria: Documents published between the years 2005 to 2020 were included. The search terms were: *exoskeleton device, rehabilitation and paraplegia,* in English; exoesqueletos, *paraplegia, lesión de médula espinal, rehabilitación*, in Spanish.

Subsequently, the electronic pages of the manufacturers were consulted.

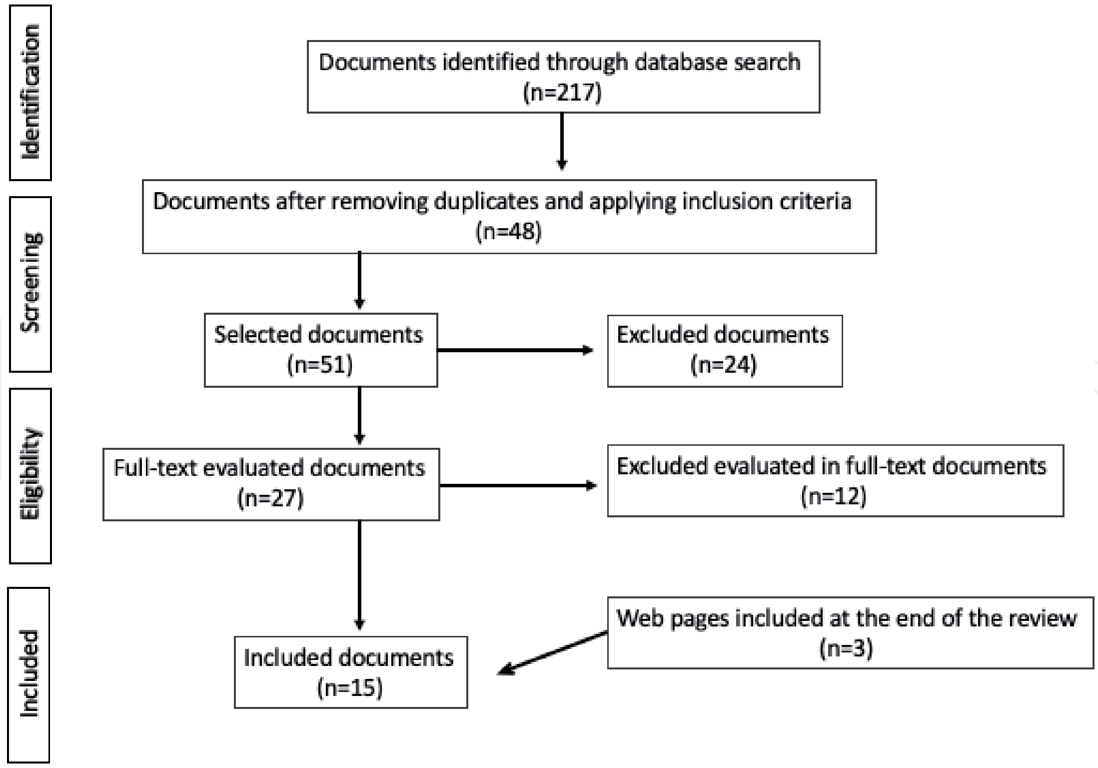

Figure 1.
Flow chart for the information selection.

Exclusion criteria: Studies published before 2005. Studies that did not include the search terms established in the inclusion criteria, incomplete or unavailable articles.

Figure 1 shows the flow diagram of the obtaining information process.

2. Exoskeletons

The operation of exoskeletons depends on a series of biometric sensors that are activated through nerve signals sent from the brain to different muscle groups so that an exact action is developed. For the creation of exoskeletons, electrical and computer patterns are used that will allow the adaptation and generation of movement in different degrees [1].

5 different models of exoskeletons were found, which are discussed below. Images of the exoskeletons are shown in **Figure 2**.

2.1 Exoskeleton Exo-H2®

It is an exoskeleton designed for the rehabilitation of adults, it is indicated for patients between 1.5 and 1.95 m in height, with a maximum body weight of 100 kg with neurological damage that prevents their motor skills [4].

It was developed by the CSIC Bioengineering Group, who granted an exclusive license to Technaid S.L. for the design, manufacture and commercial exploitation of the system.

H2 presents an open architectural design, which allows the integration with other stimulation systems, giving it an advantage over other exoskeleton models. It has motorized joints in the hips, knees and ankles, which are powered by rechargeable batteries, and it has sensors that allow a good control to perform the desired activity, whether it is walking, getting up or sitting [7].

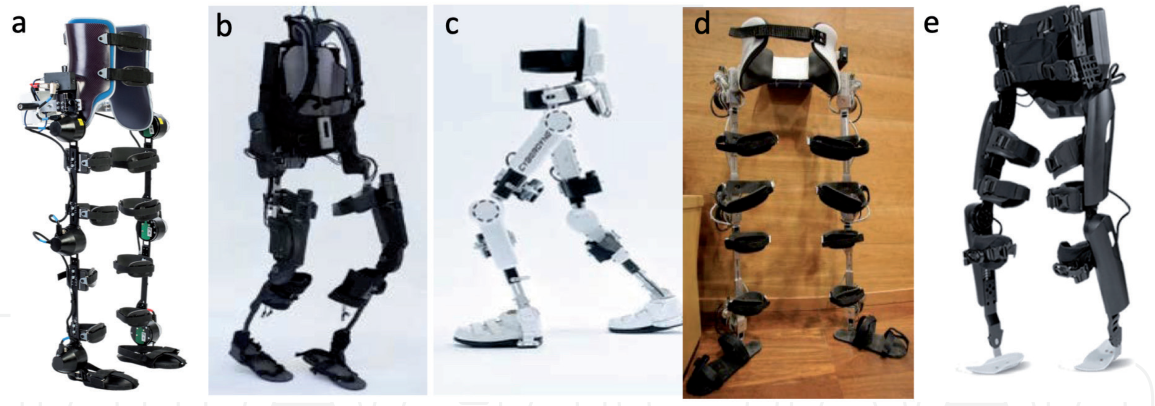

Figure 2.
Exoskeletons: a) H2, b) EKSO, c) HAL, d) KINESIS y e) ReWalk (images taken from Mardomingo-Medialdea, 2018 [7], and companies web pages).

This robotic system works through an interface that connects via Bluetooth to a smartphone; through a Wi-Fi connection, the kinetics and kinematics generated by the exoskeleton are captured and a database is formed that can be statistically analyzed [4].

The interaction between the user and the exoskeleton is very important for the comfort and safety of the users in a robotic device, as the sensors must be physically placed on the human limbs and due to several issues, specifically related to safety, comfort and reliability, placement must be taken into consideration.

The H2 exoskeleton is designed in such a way that there are no sensors physically attached to the human being, all the information indicates that the sensors placed on the exoskeleton are 6 potentiometers, 18 hall effect sensors and 4 foot switches that are used to determine parameters such as angular position and speed, and the force and interaction between the user's limb and the exoskeleton. The H2 exoskeleton is equipped with industrial precision, it includes a potentiometer used as an angular position sensor, that exhibits high linearity and long rotation life. Its gear is through a steel shaft that is coupled to a toothed pulley and a belt that is used to transmit the movement of the joint avoiding slipping and therefore an absolute loss of reference. The exoskeleton platform is equipped with two foot switches based on binary resistive sensors that allow detecting the contact between the subject's foot and the ground, these sensors are located under the heel and toe and their main objective is to detect the different phases during segmented motion [4].

The main controller is based on an H2-ARM electronic board specifically designed to control usage time. The H2-ARM plate's small size (56 x 44 mm) allows it to be placed on the exoskeleton reducing volume, as well as complexity and the difficulty of hiding wiring and connections, as well as eliminating the need for the user to carry a backpack that most lower limb exoskeletons have as a disadvantage.

During a pilot study, the H2 exoskeleton function was consistent during a clinical motion rehabilitation protocol. It was shown as a safe therapy without unwanted effects and with good tolerance by patients [8]. These results have opened the possibility of testing with a larger number of patients.

2.2 ReWalk exoskeleton

This robotic exoskeleton has the ability to use motion supports, which facilitates the autonomous movement of the patient. It was developed by ReWalk Robotics Inc [9]. Its use is designed for patients who have suffered a complete spinal cord injury between C7 and T12, which puts it at an advantage over other more limiting designs in their therapeutic applications [10].

It is an open architectural exoskeleton, which has a 28 V electric motor, located on the user's back and powered by lithium batteries with autonomy of up to three hours [9].

A novel feature of this exoskeleton is that it has inclination sensors and a wireless communicator for its control [9].

The control of the exoskeleton is given by the movements of the trunk and the movements of the center of gravity, that is, when the body moves forward, the system translates it as the beginning of the step [10].

2.3 EKSO exoskeleton

The EKSO exoskeleton, formerly known as the exoskeleton lower extremity motion system, eLEGS, was developed by Berkeley ExoWorks, a company that currently holds the name EKSO Bionics [11].

It is an open structure exoskeleton, open architectural exoskeletons make it easy to connect to other types of equipment that help with the monitoring of muscle activity [7].

This exoskeleton is designed to help people who have suffered strokes, multiple sclerosis, Parkinson's disease, or spinal cord injury below C7, limiting its use for patients with higher or invasive injuries [10].

Its operation depends on a single engine, which is located on the patient's back through a backpack, which makes it uncomfortable for some activities, however, the engine is highly efficient and favors motor skills, allowing the movement of 100% of the weight, lateral motion and squat position, a position not achieved with any other exoskeleton. It also allows the patient to sit up and return to the standing position. Among the advantages offered by this exoskeleton is that it favors the reduction of spasticity. Although the use of a backpack on the back is its greatest disadvantage because it makes it less comfortable than other models, it is still one of the most efficient and functional exoskeletons for patients with paraplegia caused by different diseases [10, 11].

2.4 HAL exoskeleton

The Hybrid Assistive Limb (HAL) exoskeleton has been developed by the Japanese company CYBERDINE Inc [12].

It is an exoskeleton with an open architectural structure.

It has electric engines located in the lateral part of the legs and arms, making this exoskeleton one of the most comfortable of those analyzed in this chapter.

The monitoring of the operation of the exoskeleton is carried out through bioelectric signal sensors located on the user's waist, connected to an interface that allows the monitoring of motor activity [5].

It is aimed at patients who have even lost all of the motor function of the lower limbs, which gives it a great advantage over other exoskeletons that are limited to the fact that the user has limited motility [10].

2.5 Kinesis exoskeleton

The Kinesis exoskeleton has been developed under the auspices of the Spanish Higher Council for Scientific Research [13].

Like the past reviewed exoskeletons, it is an open architectural exoskeleton.

This exoskeleton works with a 24 V electric engine, located on the back, a position that gives the user some discomfort, especially when changing from a standing to a sitting position [13].

NAME	EXO-H2	EKSO before eLEGS (Exoskeleton Lower Extremity Gait System)	HAL (Hybrid Assistive Limb)	KINESIS	ReWalk
DEVELOPER	CSIC Bioengineering Group, but currently the exclusive license is for Technaid S.L.	**EKSO BIONICS** before Berkeley ExoWorks	**CYBERDYNE inc.**	**CSIC** Spain	**ReWalk robotics Inc.**
TARGET POPULATION	Adults between 1.5 and 1.95 m in height, with a maximum weight of 100 kg, with neurological damage that inhibits motor skills.	It is aimed at those people with stroke, multiple sclerosis, Parkinson's or Spinal Cord Injury up to C7.	Aimed at people with walking problems due to neuromuscular pathologies such as Spinal Cord Injury.	It is aimed at people with incomplete Spinal Cord Injury capable of making short movements.	It is a lower limb exoskeleton for people with complete spinal cord injury from C7 to T12.
OPEN OR CLOSED STRUCTURE	OPEN	OPEN	OPEN	OPEN	OPEN
ENGINE AND LOCATION	Motorized joints in hips, knees and ankles	Electric engine located in the back.	Electric engine located on the side of the legs and arms, sensors on the waist. HAL-5.	24 V electric engine, located in the back.	28 V electric engine with lithium batteries with autonomy of 3 hours, located on the back.
USER-SKELETON INTERFACE	Interface that connects via Bluetooth to a smartphone.	Independent motor assistance.	Bioelectric signal sensor.	Functional electrical stimulation.	Tilt sensors. Wireless communicator.
ADVANTAGES AND DISADVANTAGES	Due to its open architecture, it can be used in combination with muscle function readers. It does not need the use of uncomfortable backpacks for the user. It can be used in patients whose paraplegia is caused by various pathologies.	Allows 100% weight shift, lateral movement and squatting position. Spasticity reduction.	It can be used even if the person has totally lost the motor function of the lower limbs.	Can effectively balance robotic performance and functional electrical stimulation during movements.	It is controlled thanks to the movement of the trunk and the movements of the center of gravity, when the body moves forward the system translates it as the beginning of the step.

Table 1.
Comparison among exoskeletons.

The user-exoskeleton interface is through functional electrical stimulation [14].

One of the great advantages of this exoskeleton is that it can effectively balance robotic performance and functional electrical stimulation during motion [10].

However, a major drawback is that it is intended almost exclusively for the usage with patients with an incomplete spinal cord injury, who are capable of short movements.

Table 1 offers a comparison of the most important characteristics of the five exoskeletons analyzed.

3. Discussion

The use of exoskeletons in the rehabilitation of patients with paraplegia shows promising results in the recovery of subjects with motor deficits [1].

There are several exoskeletons developed by different companies. These exoskeletons have evolved over time to help patients who suffer from paraplegia caused by different pathologies. To get the maximum benefit from using these devices, it is necessary for the therapist to carefully choose the appropriate device for each patient. The exoskeletons presented in this chapter have proven to be excellent aids in the partial recovery of motor skills and the improvement of spasticity, although not permanently yet, with minimal pain reported by patients who have used them. However, the cost of exoskeletons is very high, as it varies among $65,000.00 and $100,000.00, which makes it prohibitive for many patients who may require it. Clinical studies in patients have different degrees of advancement, for example: the Kinesis exoskeleton has significant potential to rehabilitate walking motion of patients with incomplete spinal cord injury. The results of tests carried out with KINESIS show that the operative controller adapted to the functional deficits of the patient as well as to voluntary actions during gait, through modulating stimulation and robotic assistance, which was the objective of the controller's design. Further developments should address the simultaneous modulation of robot stimulation and assistance based on explicit patient needs. This includes more robust methods of managing muscle fatigue. The creators foresee additional work related to various aspects of hybrid gait control: stimulation control based on estimating muscle activation, improved semi-automatic gait control, and improved muscle fatigue monitoring [15].

The EXO-H2 exoskeleton is a robust and safe exoskeleton useful for patients with partial leg weakness, while using assistive devices for the upper extremities or with the help of a healthcare professional. It can be used by patients after a stroke or traumatic injury that results in difficulties while walking. There is a preliminary study of EXO-H2 in three patients with stroke-related hemiparesis. The training was well tolerated and there were no adverse events. The authors suggest that Exo-H2 opens the opportunity to study ways to optimize a rehabilitation treatment that can be customized for each patient. These results are promising and encourage future rehabilitation training with a larger cohort of patients [9].

On the other hand, the HAL exoskeleton has been tested in eight patients recovering from hemiparetic strokes, in a study sponsored by the manufacturer and the Stockholm City Council, improving the ability to walk in the 10-meter walk test and in the categories of functional ambulation; it also improves torso posture and facilitates treadmill training, reporting the HAL exoskeleton as safe when used in conjunction with an inpatient rehabilitation program. In a current study between Dandeyd Hospital and the University of Tsukuba, the conventional gait training techniques are compared to the use of HAL in patients recovering from strokes, although the results are not conclusive yet.

The Ekso exoskeleton in its GT model is the first exoskeleton approved by the United States Food and Drug Administration (FDA). It is currently under evaluation in many centers in the United States and Europe.

The Kolakowsky-Hayner et al. [16] team found it safe to use with patients with complete thoracic spinal cord injury in a controlled environment.

The team of Kressler et al. found that people with chronic complete spinal cord injury who used the Ekso for ground walking training could achieve speeds and walking distances comparable to the averages of those with incomplete motor injuries, but there was little change in the activation of the leg muscles [17].

Ekso may help stroke patients stand longer and take more steps [9].

Finally, the ReWalk exoskeleton has proven to work well in patients with spinal cord injury. Outcomes of patients who have been able to walk independently have been documented. In the United States it began to be used in the middle of this decade; the United States Veterans Administration has implemented the use of ReWalk in veterans with paraplegia; and its use in patients recovering from cerebrovascular accidents and people with multiple sclerosis is currently under investigation [9].

4. Conclusions

The use of robotic technology as support for the rehabilitation of patients with paraplegia is a very important tool, which should be considered as part of recovery plans, improving the quality of life of users who require them. However, it is important to note that although it has great advantages for users, the cost of these exoskeletons is so high that it becomes difficult to be provided to all those patients who need them, besides there are also some models that are in early preliminary studies to be still considered for use in regular clinical practice.

4.1 Perspectives

In the next 10–15 years, another important area of development will be modular robotics, specifically exoskeletons made for unique joints such as the hip, knee or ankles, as well as the so-called "soft robotics" that use non-rigid materials, in custom positions to provide movement for people with different physical limitations that do not fit in the current rigid robots. An example of this type of modular robot is the Honda Strike Management Assist (SMA), which fits around a person's waist and thighs like a belt and provides assistance to people with weakened leg muscles. Weighing approximately 2.8 kg, the SMA is much smaller and lighter than other exoskeletons. It is designed to help users regulate their walking pace and lengthen their stride, particularly for people who can walk but have mild gait deficiencies due to aging or other medical conditions. Researchers at the Chicago Rehabilitation Institute are currently evaluating the use of SMA with task-specific training, comparing it to traditional physical therapy in the outpatient setting, for people who have suffered a stroke. Additionally, soft robotics, an emerging area focused on developing systems that are lighter and more flexible to help people with weakened upper or lower limbs, is also evolving. Currently, groups such as Harvard University [18], Yale University, and ETH Zurich are working on soft material technologies that are made up of polymers, gels, and soft microfluidic electronics that exhibit significant elasticity with the potential to enhance the utility of wearable robotics. Finally, systems that combine functional electrical stimulation, pattern recognition, and brain-machine interfaces are also likely to emerge. All of these technologies have the potential to work separately or synergistically with exoskeletons, depending on a person's level of injury and rehabilitation goals [9].

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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